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Interaction between Douglas-fir Regeneration and Frost in Central British Columbia

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Robert M. Sagar and Michaela J. Waterhouse

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ABSTRACT

In the Sub-Boreal Spruce dry warm (SBSdw) biogeoclimatic subzone, on the Interior Plateau of British Columbia, frost is a limiting factor for the establishment and growth of Douglas-fir (*Pseudotsuga menziesii*) in clearcuts. A replicated research trial, using a uniform shelterwood silvicultural system, involved harvesting in three passes over a 20-year period to test how residual basal area retention affected establishment, growth, and condition of natural regeneration. Starting with even-aged stands of mature Douglas-fir averaging 61 m^2/ha, a preparatory cut in 1991 resulted in 40 m^2/ha retention, which was followed by a regeneration cut in 2001 that reduced the basal area to 20 m^2/ha. Final harvesting took place in 2011, which reduced the basal area of mature trees to 0 m^2/ha in the previously uncut control and shelterwood treatments. Microclimate monitoring stations were installed at three research sites in 2012 and were monitored for 5 years to compare vertical air temperature profiles in the former 60 m^2/ha uncut controls (**60**) and in the former 20 m^2/ha shelterwoods (**20**) at each site.

In the **20** treatment units, the percent cover and modal height of the tall (> 2 m) shrub layer, primarily Douglas-fir and hybrid white spruce (*Picea glauca* × *engelmanni*) regeneration, was much greater (27–53%, 3.5–5.7 m) than in the **60** treatment units (< 10%, 3.1–3.6 m) that had no previous harvesting history.

Air temperature profile data at 15, 40, 75, and 150 cm above ground showed that strong temperature inversions frequently occurred in the **60** treatment units on clear, calm nights, while well-mixed, neutral (isothermal) profiles were observed in the **20** treatment units (2012–2016). This led to more frequent frosts, greater duration of subfreezing minutes, and lower extreme air temperatures during the growing season at the lower measurement heights in the **60** treatment units. We assessed frost damage on planted Douglas-fir seedlings in two of the **60** treatment units. Nighttime minimum air temperatures were as low as –8.1°C on the night of June 4–5, 2014 for the 15-cm measurement height in the **60** treatment units, which caused frost damage on 64% of the seedlings. In contrast, tall regeneration in the **20** treatment units showed no apparent frost damage.

Over the 25-year study, air temperature data were collected during three time periods to compare various treatments (uncut, clearcut, and shelterwood). When combined for one of the research sites (Beedy Creek), they clearly showed the relationship between overstorey forest cover and frost frequency. Frost occurred frequently (up to 12 occurrences during the May 15–July 31 period) following harvesting of the **60** treatment units in 2011, compared with less than one occurrence per season in the same location prior to harvesting (1993–1995). The frequency of frost occurrences increased from less than one per season (1993–95) to about seven per season (2012–16) in the same **20** treatment unit after basal area was reduced to 0 m^2/ha in 2011. However, the moderate frost frequency that occurred in the shelterwood **20** treatment units following final harvesting in 2011 was of little consequence to the tall, well-established Douglas-fir regeneration.

A shelterwood system that uses a regeneration cut (or in combination with a preparatory cut) can lower the frequency and duration of frost events, as well as moderate extreme temperatures during the establishment phase,

and after the final cut, can leave a well-developed regeneration layer that can moderate and survive frost.

ACKNOWLEDGEMENTS

This experiment was approved as Experimental Project 1104.01 in 1990 by the former British Columbia Ministry of Forests and Range Research Branch. This research project involved a partnership between the research staff in the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), Cariboo Region; West Fraser Timber Company (Williams Lake Division); and the University of British Columbia Alex Fraser Research Forest. This phase of the microclimate project was funded by FLNRORD. We would like to thank Craig Sutherland, Ken Day, and Chris Burger, who designed and established the uniform shelterwood project, and the researchers, Teresa Newsome, Nola Daintith, and Phil Burton, who have worked on the project over the years.

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1 INTRODUCTION

The prevailing forestry practice in the Sub-Boreal Spruce dry warm subzone, Horsefly variant (SBSdw1) east of Williams Lake, British Columbia in the late 1980s was to clearcut Douglas-fir leading stands that had components of lodgepole pine (*Pinus contorta*) and hybrid white spruce (*Picea engelmannii* × *glauca*), then plant primarily lodgepole pine because Douglas-fir was difficult to regenerate in frost-prone clearcuts. Recognition that it would be desirable to successfully regenerate Douglas-fir to maintain biodiversity, mule deer winter range, and higher timber values, while observing that natural Douglas-fir regeneration was present in some mature stands in the SBSdw1, led to the conception of this research project. The project goal was to develop a shelterwood silvicultural system that could successfully regenerate even-aged Douglas-fir forests (Sutherland et al. 1990; Waterhouse 2001).

The efficacy of shelterwood and other silvicultural systems that feature retention of mature trees for moderating nighttime minimum near-ground air temperatures has been well documented (Hungerford and Babbit 1987; Groot and Carlson 1996; Langvall and Orlander 2001). Conversely, clearcut areas in this region have been shown to be extreme environments with frequent potentially damaging growing-season frosts (Stathers 1989; Steen et al. 1990; Sagar et al. 2005).

This uniform shelterwood research trial entailed harvest entries in 1991, 2001, and 2011. The first two harvest entries reduced basal area in some treatment units, while maintaining the uncut control treatment units. The final harvest entry in 2011 removed all remaining mature trees from the treatment units, including previously uncut controls. Establishment and growth of natural regeneration were measured throughout the study. Burton et al. (2000) and Waterhouse and Newsome (2006) looked at factors that affected natural regeneration through the first 15 years of the study, and found that natural regeneration of Douglas-fir was successful in treatments with retained basal areas of 15, 20, and 30 m^2/ha. The established regeneration and microclimate were subsequently followed post–final harvest to see how they responded to the final overstorey removal.

The microclimate of near-ground air temperature and frost incidence in the various shelterwood basal area retention treatments was monitored during three separate time intervals: 1991–1995 (Burton et al. 2000), 2001–2008 (Sagar and Waterhouse 2010), and 2012–2016. Sagar and Waterhouse (2010) demonstrated that retained basal area densities as low as 15 m^2/ha significantly reduced frost incidence and severity compared with a nearby clearcut area. They also showed that the duration of near-ground frost events was correlated with sky view factor.

In the shelterwood system, the canopy of the retained mature trees modifies the environment within and beneath it (Sagar and Waterhouse 2010). Sagar and Waterhouse (2015) showed that over time, as natural lodgepole pine regeneration grows in clearcut and small partial cut openings, the frequency and severity of near-ground growing-season frosts begins to decrease. Špulák and Souček (2010) found that air temperatures within the foliage of an individual 2.5-m tall Norway spruce (*Picea abies*) were moderated compared with those outside the foliage. In this study, we examined how the shrub layer, composed mostly of Douglas-fir and hybrid white

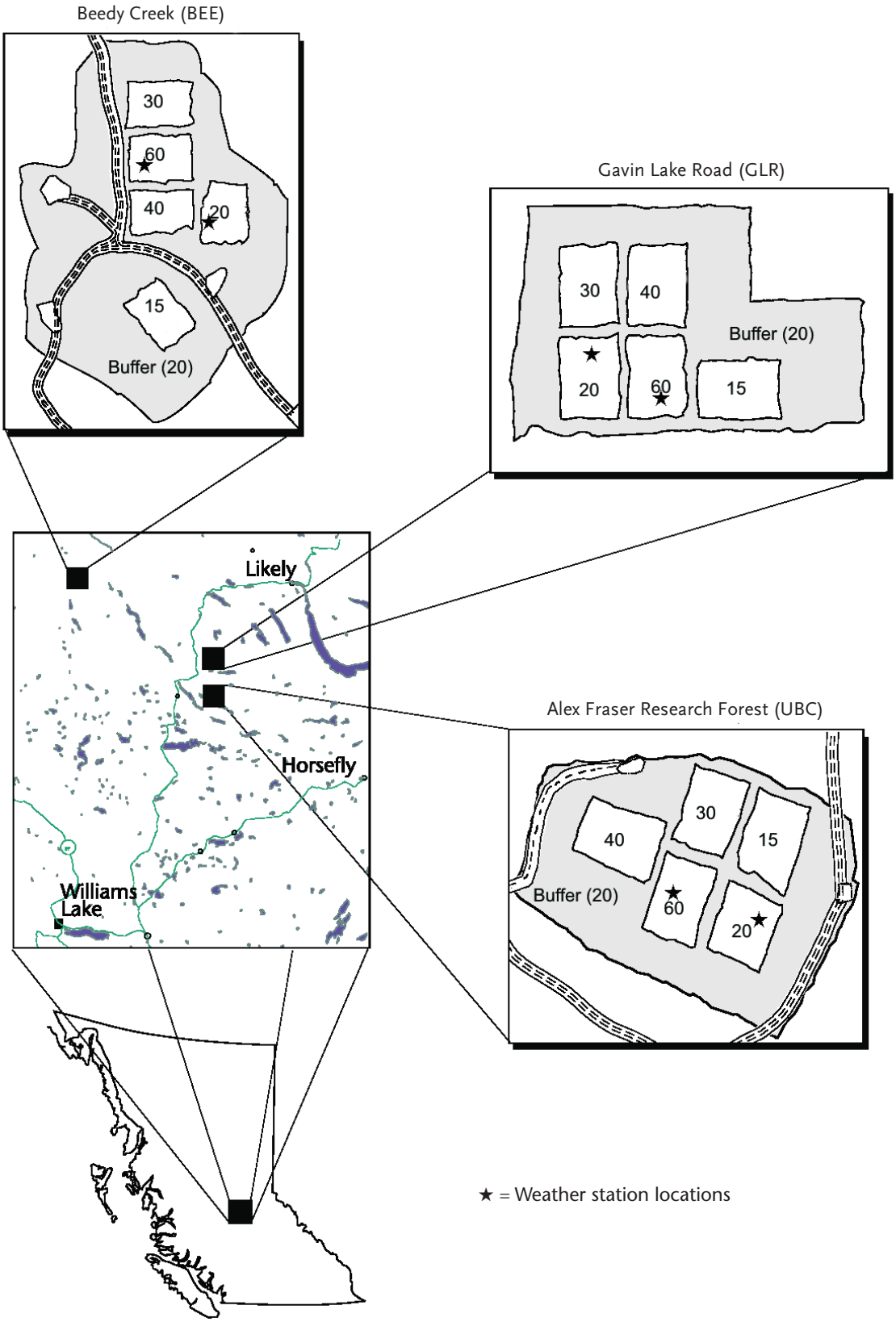


FIGURE 1 *Location of study sites and treatment units within each site. The approximate dimensions of treatment units are 140 × 100m.*

spruce regeneration, modifies microclimate in the absence of a mature forest overstorey. In this case, the top of the regeneration replaces the ground surface as the effective radiative exchange surface where maximum cooling occurs. Parker (1995) calls the canopy top the "active" layer for radiative exchange, which cools rapidly on clear, calm nights and often forms an inversion layer above the canopy.

1.1 Microclimate Study Objectives

The final harvest of the treatments in the research trial in 2011 resulted in two types of clearcuts: one where there was a short, poorly developed shrub layer (reflecting its history as a previously uncut control treatment), and the other with a taller, well-developed shrub layer (resulting from the regeneration cut shelterwood treatment). Our overall objective was to compare the vertical profiles of air temperature between the clearcut control treatment (termed **60**) and the clearcut shelterwood treatment (termed **20**). Specific objectives over the 2012–2016 monitoring period were to:

- compare the incidence and severity of growing-season frosts during the bud flush (May 15–July 31) and bud set (August 15–September 30) periods between the clearcut control treatment and clearcut shelterwood treatment;
- investigate the effects of regeneration height and cover on the vertical profile of minimum air temperature;
- examine the effect of the timing and severity of growing-season frosts on planted Douglas-fir seedlings in the clearcut control treatments (2012–2016); and
- compare near-ground growing-season frost incidence in the various treatments during three study periods between 1991 and 2016.

2 METHODS

2.1 Study Area

The three replicated study sites are located on the Interior Plateau, north to northeast of Williams Lake, British Columbia (Figure 1). The Gavin Lake Road (GLR) and Alex Fraser Research Forest (UBC) sites are located near Gavin Lake, within 2 km of one another, while the Beedy Creek (BEE) site is located about 25 km to the northwest of the Gavin Lake sites. Site elevations range from 820 to 1020 m. The treatment units within each site are very similar in terms of location (latitude, longitude), elevation, slope, and aspect (Table 1).

All sites are located in the Sub-Boreal Spruce dry warm biogeoclimatic subzone, Horsefly variant (SBSdw1) (Steen and Coupé 1997). The dominant site series is zonal (01 SxwFd – Pinegrass), and the soil type is a moderately well-drained Luvisol with a Mor humus form (Burton et al. 2000).

In 1991, the original stands were a mix of mature (118–138 year-old) Douglas-fir (65–83% by volume), followed by lodgepole pine, hybrid spruce, subalpine fir (*Abies lasiocarpa*), birch (*Betula papyrifera*), and aspen (*Populus tremuloides*) (Burton et al. 2000). The mean pre-harvest basal area was approximately 61 m^2/ha across the three sites.

2.1.1 Study design and treatments The original study design was a randomized complete block consisting of five 1.4-ha treatment units at each of the

TABLE 1 *Site descriptions, including treatment unit (TU), elevation, slope, aspect, and location*

Site[a]	TU	Elevation (m)	Slope (%)	Aspect (°)	Latitude	Longitude
GLR	20	1000	12	225	52°29′40″	121°47′38″
GLR	60	1000	3–5	225	52°29′37″	121°47′33″
UBC	20	992	0	flat	52°28′43″	121°47′26″
UBC	60	995	2–4	270	52°28′46″	121°47′33″
BEE	20	858	2–5	270	52°38′28″	122°06′24″
BEE	60	848	7–10	270	52°38′30″	122°06′33″

a GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest; BEE: Beedy Creek.

three sites. The overall size of each study site ranged from 20 to 40 ha, with the treatment units separated by 20-m buffer strips and an overall 100-m buffer outside all treatment units.

The five treatment units were designed to compare the effects of residual basal area retention (60, 40, and 30 m^2/ha) and method of harvesting (fellerbuncher versus hand-felling) (Burton et al. 2000). The first harvest was conducted in 1991, and focussed on removing pine, spruce, and smaller-diameter Douglas-fir. The buffer area around the treatment units was also thinned to 40 m^2/ha using a fellerbuncher. In 2001, the preparatory cut (40 m^2/ha) and regeneration cut (30 m^2/ha) treatments that were originally made by the fellerbuncher in 1991 were thinned from below a second time, again with a fellerbuncher. In the 40 m^2/ha treatment units and buffers, basal area was reduced to approximately 20 m^2/ha (regeneration cut), while the 30 m^2/ha treatment units were thinned to approximately 15 m^2/ha (second regeneration cut). The intention of the second harvest entry was to improve the condition and growth of the established regeneration by reducing overstorey competition for light, moisture, and nutrients, while retaining a measure of frost protection. The final harvesting entry occurred in 2011, when all treatments were clearcut with a fellerbuncher, which reduced the basal area of mature trees to 0 m^2/ha.

Table 2 summarizes the logging history and treatment names used during the different phases of this study. It was decided to use treatment names that were descriptive rather than assigned numbers and letters. This resulted in some changes to names over the course of the three study phases. The subject of this paper is primarily the microclimate conditions for a 5-year period, 2012–2016, after the final harvest in two of the original treatments. The treatments monitored were the original uncut control (**60**) and regeneration shelterwood (**20**) at each of the BEE, GLR, and UBC sites. The final harvest removed all the overstorey trees on both treatments but left poorly developed regeneration layers in the **60** treatments and well-developed regeneration layers in the **20** treatments. It should be noted that we have dropped the units (m^2/ha) to avoid any implication that **20** and **60** reflect the current basal area.

2.2 Vegetation Data Collection

2.2.1 Vegetation cover and height assessment Vegetation sampling was conducted on eight 50-m^2 circular plots (3.99-m radius) that were laid out on a grid between skid trails within each 1.4-ha treatment unit in 2015. Vegetation was divided into the following four layers for sampling purposes:

B1: tall shrubs ≥ 2.0–10 m (includes tree regeneration)
B2: low shrubs < 2.0 m (includes tree regeneration)
C: herbaceous layer (includes dwarf shrubs < 15 cm)
D: mosses, lichens, and liverworts

Ocular estimates were made of percent cover for each layer as a whole and for individual species within the layer. The layers and species were assessed independently, so there was overlap between layers and between species. Modal height was also measured for each layer. In this study, we were interested mainly in the B1 and B2 layers, which were tall enough to influence air temperature measurements between 15 and 150 cm above the ground.

TABLE 2 *Shelterwood treatment names in 1991, 2001 and 2011. Shelterwood treatment names were based on residual basal area (RBA) retention targets and harvesting methods in 1991 and 2001. In 1991, two clearcuts near the Beedy Creek and UBC trial blocks were selected for microclimate and planted stock studies. Three new clearcut blocks, near the trial blocks, were selected in 2001 for Phase 2 planted stock and microclimate studies. All treatments were clearcut in 2011, which reduced the basal area to 0 m²/ha, and the 2011 name reflects the basal area during the 2001–2011 period.*

1991			2001			2011	
Treatment	**Treatment name**	**Target RBA (m²/ha)**	**Treatment**	**Treatment name**	**Target RBA (m²/ha)**	**Treatment**	**Treatment name**
no–harvest control	100% RBA	60	no–harvest control	60	60	clearcut	60
preparatory cut – hand–felling	70% RBA–HF	40		40		clearcut	
preparatory cut – fellerbuncher	70% RBA–FB	40	regeneration cut	40(20)	20	clearcut	20
regeneration cut – hand–felling	50% RBA–HF	30		30		clearcut	
regeneration cut – fellerbuncher	50% RBA–FB	30	2nd regeneration cut	30(15)	15	clearcut	
clearcut	0% RBA	0		0		none	

2.2.2 Frost damage assessment on planted stock During the spring of 2012, a 50/50 mix of Douglas-fir and spruce seedlings was planted on the GLR **60** and UBC **60** treatment units and skid trails in all three sites to ensure stocking. Trees were planted, where possible, on microsites that were thought to reduce frost damage, such as next to stumps and logs, on small slopes, and at high points. This provided an opportunity to assess Douglas-fir performance in a clearcut environment. All Douglas-fir seedlings in 15 plots (5.64-m radius) were assessed. Eighty trees were sampled in the UBC **60** treatment unit, and 75 were sampled in the GLR **60** treatment unit.

Sampling was conducted during late summer or early autumn of each year between 2012 and 2016. Seedlings were assessed for size, overall vigour, and various types and causes of damage. For this study, we were most interested in frost damage. Indications of frost damage on seedlings included forked stems, necrotic or chlorotic foliage, dead buds, and absent needles.

2.3 Micrometeorological Instrumentation

Micrometeorological measurements were taken during three distinct periods of this study: 1991–1995, 2001–2008, and 2012–2016. Descriptions of the methods used during the 1991–1995 and 2001–2008 measurement periods are provided in Burton et al. (2000) and Sagar and Waterhouse (2010), respectively. For the 2012–2016 measurement period, the **60** and **20** treatments at BEE, GLR, and UBC were instrumented. Instrumentation at each site consisted of three vertical arrays of air temperature sensors mounted on metal fence posts. Sensors were mounted at heights of 15, 40, 75, and 150 cm above the ground. Air temperature measurements were replicated three times at each height except 150 cm, where they were replicated only twice due to the limited number of datalogger channels available.

As previously mentioned, all mature trees had been removed from these sites leaving only shrubs, along with varying heights and densities of natural regeneration. Skid trails (approximately 4 m wide) were parallel to each other at a spacing of about every 20 m. Skid trails were generally open with only small amounts of natural regeneration and some planted seedlings. All sensor array posts were located off skid trails at the three **20** treatment units. Some sensor array posts were located on skid trails at the **60** sites, as they were representative of the treatment in terms of shrub layer development.

Air temperature sensors were unshielded, twisted, and soldered 30AWG Chromel-Constantan (Omega Engineering Inc., Laval, Que.) fine-wire thermocouples. Reference temperatures for the thermocouple measurements were measured with thermistors (YSI Inc., Yellow Springs, Ohio, Model 44002A) mounted on the datalogger wiring panels.

2.3.1 Data collection Data were collected using CR10 dataloggers and SM192 storage modules (Campbell Scientific Canada Corp., Edmonton, Alta.). By the start of the 2014 growing season, all CR10 dataloggers and SM192 storage modules were replaced with extended-memory Campbell Scientific CR10X dataloggers. The dataloggers were housed in sealed fibreglass enclosures, which were covered by wooden boxes. The dataloggers took readings from all sensors, once per minute during the growing season and once every 3 minutes during the rest of the year. Daily maximum, minimum, and average values were recorded for all sensors. Hourly averages of air temperature were recorded. The total number of 1-minute (summer) and 3-minute periods (winter) when the air temperature was less than 0°C (Σt_o) were recorded daily for each sensor.

2.4 Data Analysis

Snow cessation dates were determined by examining the diurnal 15-cm air temperature range at each sensor array. Snow-covered sensors have a small diurnal temperature range, with temperatures at or below 0°C. When snowmelt exposes the sensor to the air, there is a sudden increase in the diurnal temperature range, with temperatures > 0°C being possible. The date when this occurs is referred to as the snow cessation date. Since the sensors were 15 cm above the ground, the actual snow-free date at a given location will be later than the snow cessation date determined using 15-cm air temperature. For this study, treatment average snow cessation dates were determined based on temperature data from all sensor arrays.

Analysis of air temperature data focussed on growing-season microclimate conditions at the sites. Two periods when seedlings are considered susceptible to frost damage were defined as the bud flushing (May 15–July 31)

and bud set (August 15–September 30) periods. The primary variable of interest was daily minimum air temperature (T_a) at each height along the vertical profile. Total numbers of frosts ($T_a < 0°C$) and severe frosts ($T_a \leq -4°C$) were tabulated for the periods of interest at each profile height and were averaged across the replicates. The duration of temperatures below 0°C in minutes (ΣT_o) was totalled for periods of interest at each height and was averaged over the replicates.

3 RESULTS

3.1 Vegetation Cover

Figure 2 shows mean modal height and percent cover of vegetation in each treatment, measured in 2015 for tall (2–10 m) and low (< 2 m) shrub layers. Natural regeneration of Douglas-fir and hybrid white spruce made up a large proportion of the shrub layers (especially the tall shrub layer at the **20** treatments). For example, at BEE **20**, the combined cover of Douglas-fir and spruce was approximately 66%.

The combined percent cover of the tall and low shrub layers was significantly higher in the **20** treatments—almost 70% at BEE and GLR—compared with < 50% for the **60** treatments. Tall shrub percent cover was also much higher in the three **20** treatment units, ranging from 27 to 53%, compared with approximately 10% in each of the paired **60** treatments. Tall shrub cover at BEE **20** was significantly higher than that at the other **20** treatment units.

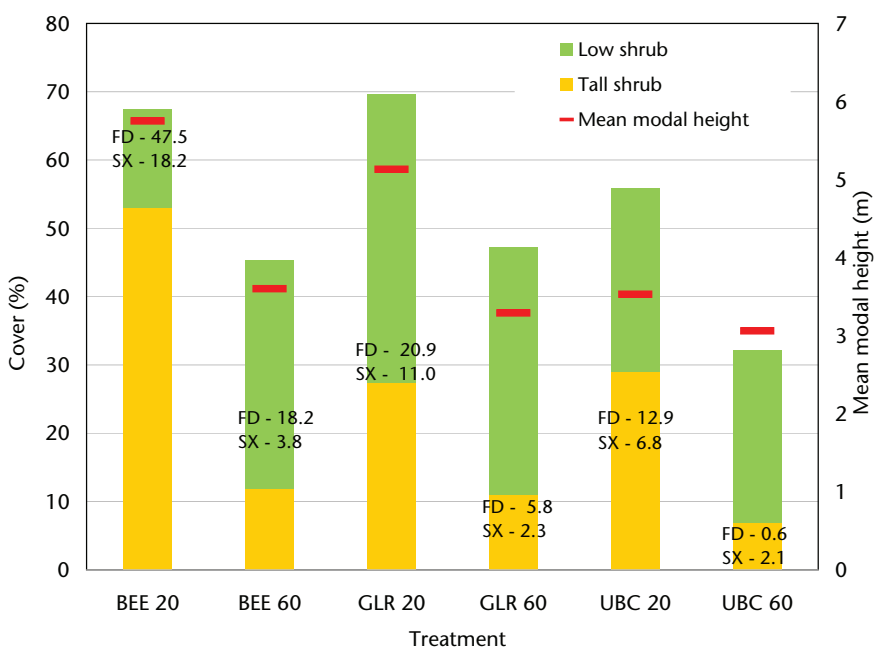


FIGURE 2 *Mean modal height and percent cover of the tall shrub (>2m) and low shrub (< 2m) layers at each treatment unit in 2015. Percent cover of Douglas-fir (FD) and spruce (SX) from both layers combined is shown as text at the approximate y-axis value. BEE: Beedy Creek; GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest*

BEE **20** also had the tallest regeneration, with a mean modal height of 5.75 m in 2015. Tall shrubs at the BEE **20** and GLR **20** treatment units were approximately 2 m taller than those in their corresponding **60** treatments. Tall shrubs at the UBC **20** treatment unit had a mean modal height of 3.53 m, which was only about 0.5 m taller than those at the UBC **60** treatment unit; however, percent cover of tall shrubs was only about 7% at the **60** treatment unit compared with 29% at the **20** treatment unit.

3.2 Snow Cessation Dates

Snow cover cessation dates for snow depths > 15 cm are shown in Table 3 for each year from 2013 to 2016. Snow cover lasted well into April in 2014 in all treatment units, while in 2015 and 2016, snow cover dropped below 15 cm as early as mid to late February at some locations. On average, snow cover ablated 1–2 weeks earlier at the UBC treatments than at the GLR and BEE treatments. Sagar and Waterhouse (2010) also reported this finding for the 2002–2008 period.

TABLE 3 *Snow cover cessation dates for snow cover > 15 cm (2013–2016) based on the diurnal range of 15–cm air temperature (mean date averaged over three posts or all posts with good data)*[a]

Year	GLR 20	GLR 60	UBC 20	UBC 60	BEE 20	BEE 60
2013	Apr. 4	Apr. 5	Mar. 30	Mar. 30	Mar. 31	Mar. 27
2014	Apr. 22	Apr. 19	Apr. 10	Apr. 10	Apr. 11	Apr. 10
2015	Mar. 9	Feb. 21	Feb. 13	Feb. 13	Mar. 10	Mar. 10
2016	Mar. 26	Mar. 16	Feb. 29	Feb. 24	Feb. 24	Feb. 21
Mean	**Mar. 31**	**Mar. 24**	**Mar. 14**	**Mar. 13**	**Mar. 20**	**Mar. 18**

a GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest; BEE: Beedy Creek.

3.3 Air Temperature

Understanding the effects of subfreezing air temperatures on seedlings is more complex than just considering extreme minimum air temperatures. Both the duration of subfreezing temperatures and the number of events where air temperature was < °0C (frosts) and ≤ –4°C (severe frosts) may be important in evaluating possible seedling damage, and may help distinguish which locations and measurement heights represent the harshest environments. Statistics related to frost (2012–2016) are presented in Appendix 1 (bud flush) and Appendix 2 (bud set).

Figure 3 shows the average duration of subfreezing minutes (2012–2016) for each site and treatment during the bud flush and bud set seasons. The pattern of decreasing subfreezing minutes with increasing height above the ground suggests that inversion conditions existed. This pattern was strongest in the **60** treatment units, weaker in the GLR and UBC **20** treatment units, and non-existent in the BEE **20** treatment unit. In all cases, at 15 cm above the ground, there were more subfreezing minutes in the **60** treatment units than in the **20** treatment units. This pattern persisted for the 40 and 75 cm heights at the BEE and UBC sites; however, at the GLR site, subfreezing minutes in the **20** treatment unit exceeded those in the **60** treatment unit for all measurement heights except 15 cm. There were more frost minutes at the 150 cm heights in the **20** treatment units than in the **60** treatment units, which indicated that there was some pooling of cold air on the surface of the taller, higher-cover shrub layer.

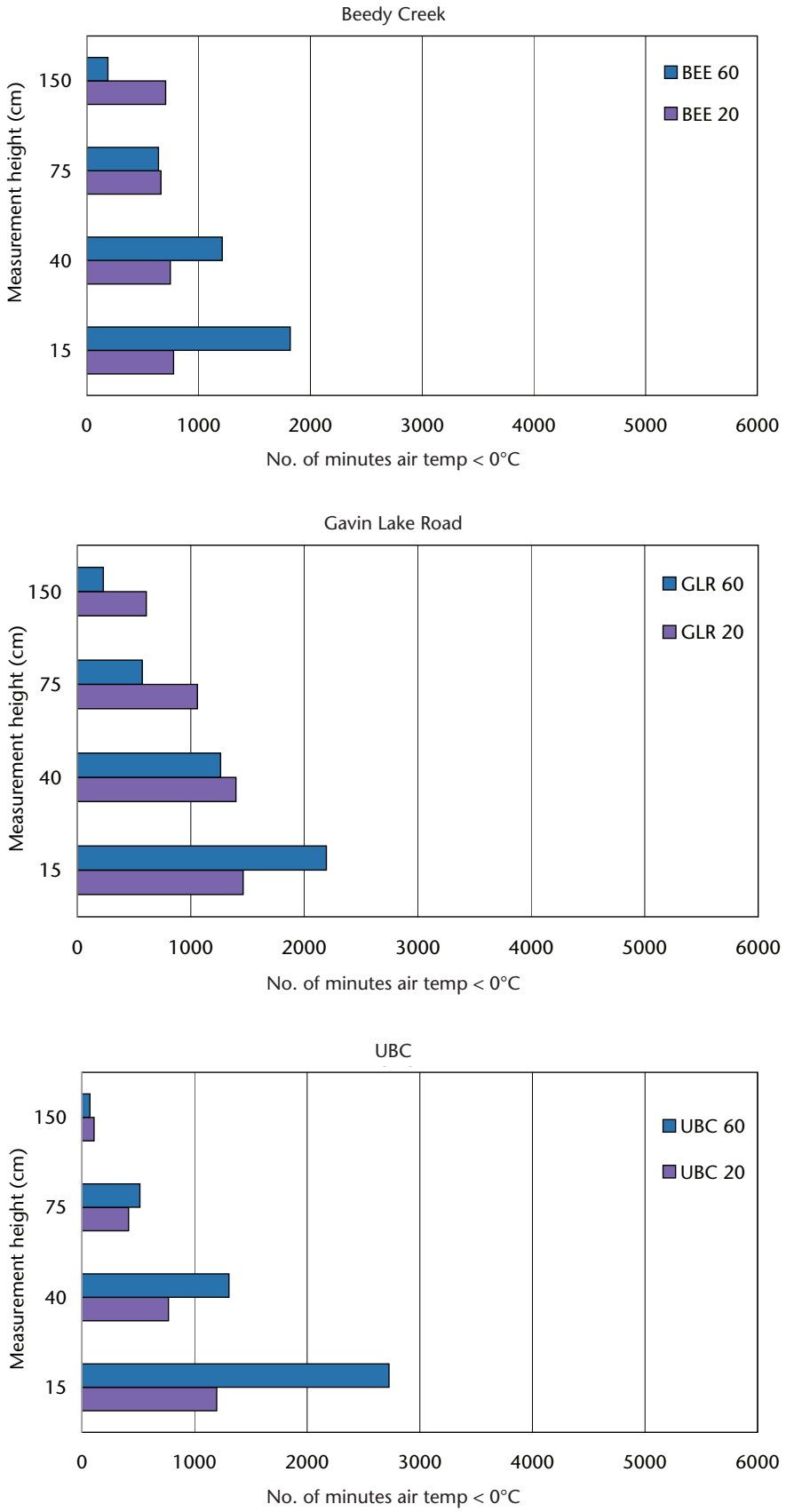


FIGURE 3 *Seasonal average (2012–2016) number of minutes with air temperature < 0°C for the bud flush (May 15–July 31) and bud set (August 15–September 30) periods at each site and treatment.*

Bud flush

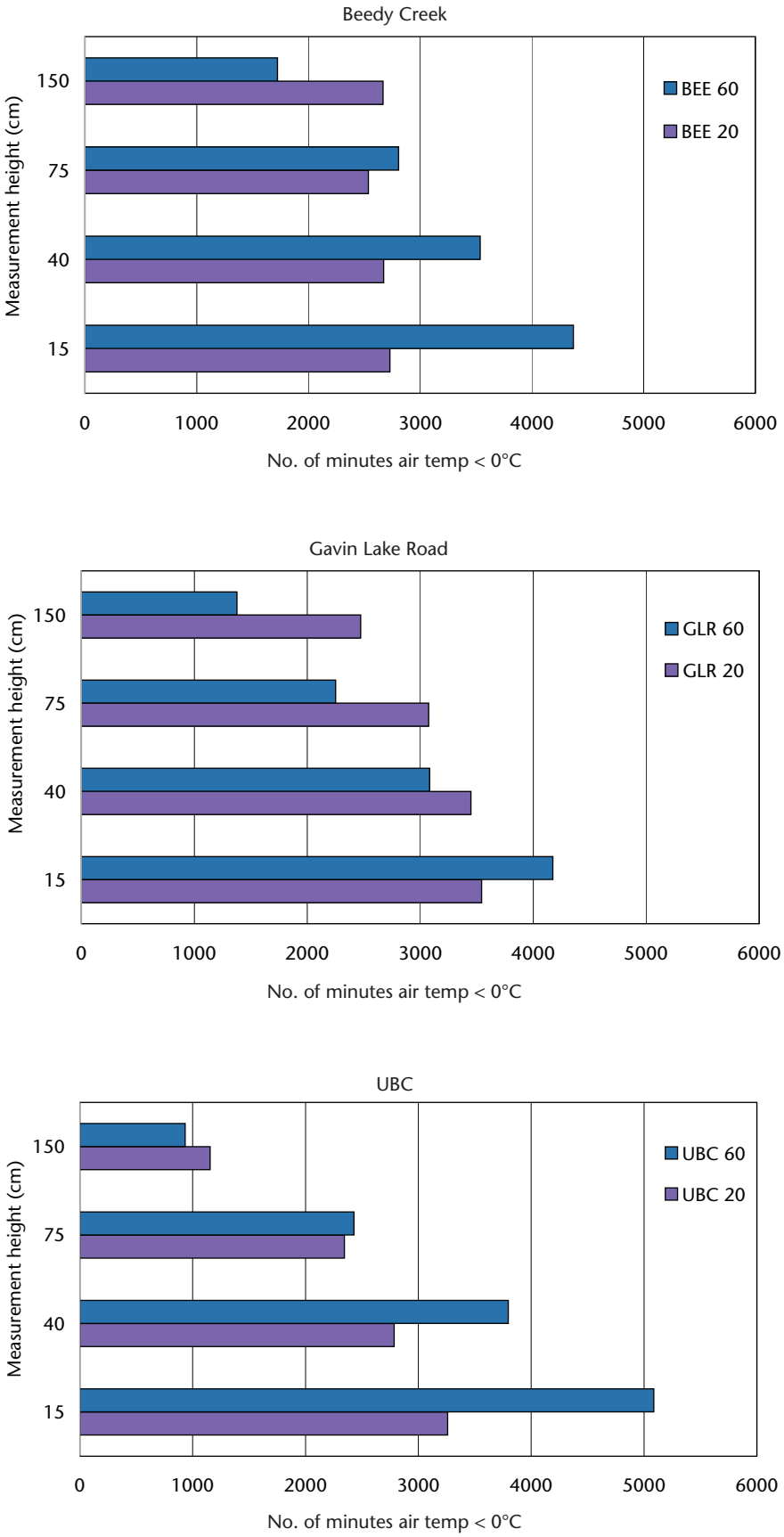


FIGURE 3 *Continued*

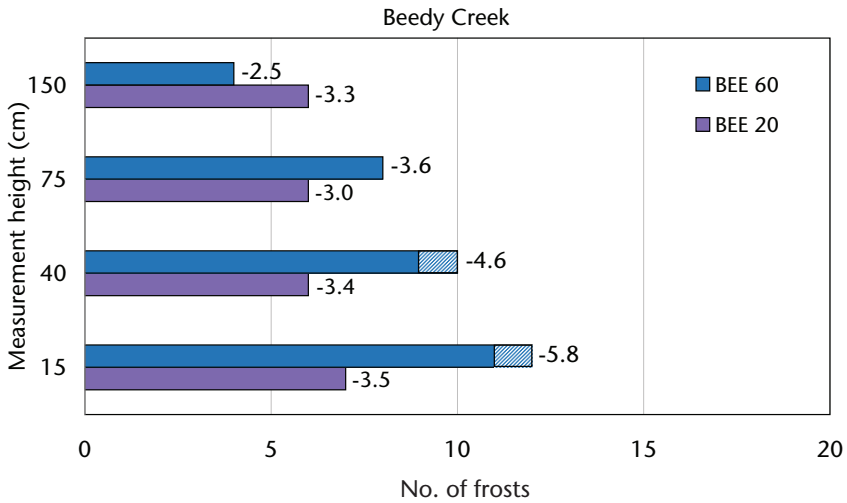
Bud set

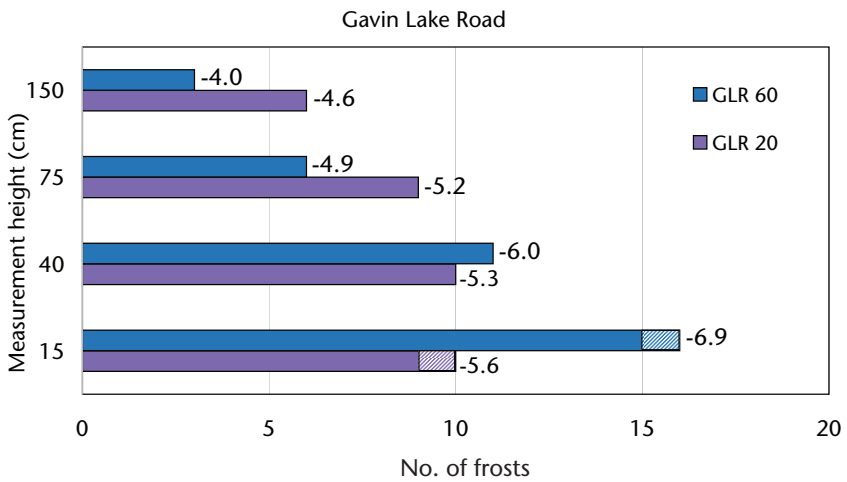
Figure 4 shows the average number of frosts and severe frosts (2012–2016) as well as extreme minimum air temperatures for each site and treatment during the bud flush and bud set seasons. The patterns are similar to those shown in Figure 3 for duration of subfreezing minutes, with strong inversions in all of the **60** treatment units and no inversions in the GLR and BEE **20** treatment units. While subfreezing minutes and frost (< 0°C) numbers for the 40 and 75 cm measurement heights at GLR **20** equalled or exceeded those at GLR **60** during the bud set period, severe frosts (≤ –4°C) were more frequent and extreme minimum air temperatures were lower in the GLR **60** treatment unit.

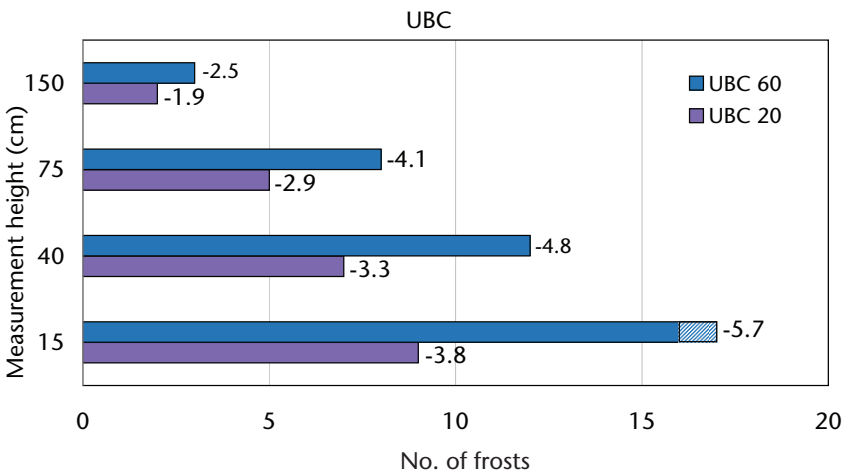
In general, severe frosts were more numerous and extreme temperatures were lower in the **60** treatment units than in the **20** treatment units, except at some of the 150 cm measurement heights and at the GLR site for the 40 and 75 cm heights during the bud flush period. Severe frosts were uncommon during the bud flush period: they occurred during only one of the five growing seasons (2014) (Appendix 1) and only at the 15- and 40-cm sensors. Severe frosts occurred more frequently during the bud set season: they occurred at least once over the 4 years at every sensor position on both the **60** and **20** treatments (Appendix 2). The lowest extreme minimum air temperatures were recorded during the bud set period in the **60** treatment units (–8.0 to –10.5°C).

To illustrate the effect of vegetation cover on air temperature, Figure 5 shows the duration of subfreezing minutes for individual sensor arrays in the GLR **20** treatment during the bud flush and bud set seasons of 2013 and 2016 (totals were an average of the two seasons that had complete data). The photos show individual sensor arrays and their surroundings. Sensor arrays 2 and 3 were located well off the skid trail within an area of dense, tall natural regeneration; sensor array 1 was just off the skid trail and had scattered larger coniferous regeneration behind it but only low shrubs and herbaceous vegetation in front of it facing the skid trail. In a pattern reminiscent of the differences seen between **60** and **20** treatments, sensor array 1 accumulated significantly more subfreezing minutes than the other two sensor arrays, especially at the 15- and 40-cm measurement heights. Frost and severe frost numbers were also higher for sensor array 1: it recorded one to five more frosts and up to one more severe frost per season. Seasonal extreme minimum temperatures were 0.4–1.2°C lower at sensor array 1. Sensor arrays 2 and 3 showed little evidence of an inversion, with nearly equal numbers of subfreezing minutes at all heights. For sensor array 1, subfreezing minutes decreased with increasing measurement height. Although differences in the vegetation cover surrounding sensor arrays at the UBC **20** and BEE **20** treatment units were more subtle than at GLR **20**, the data suggested that there were some similar relationships between vegetation density and minimum air temperatures. These results corroborate the conclusion that the relative cover of the shrub layer in the **60** and **20** treatment units affected the duration of subfreezing air temperature, and the number and severity of frosts.

In Figure 6, the subfreezing minutes were totalled for each day during the 2012–2016 period, at the 15 cm height, by treatment unit. Frost occurred on more days and was of longer duration at the **60** treatment units than at the **20** treatment units. Some frost days occurred during mid-summer at the **60** treatment units, especially at GLR and UBC, but they occurred only briefly on 2 days at the **20** treatment units. While some frost occurred during the late May and early June period at the **20** treatment, the number of days and

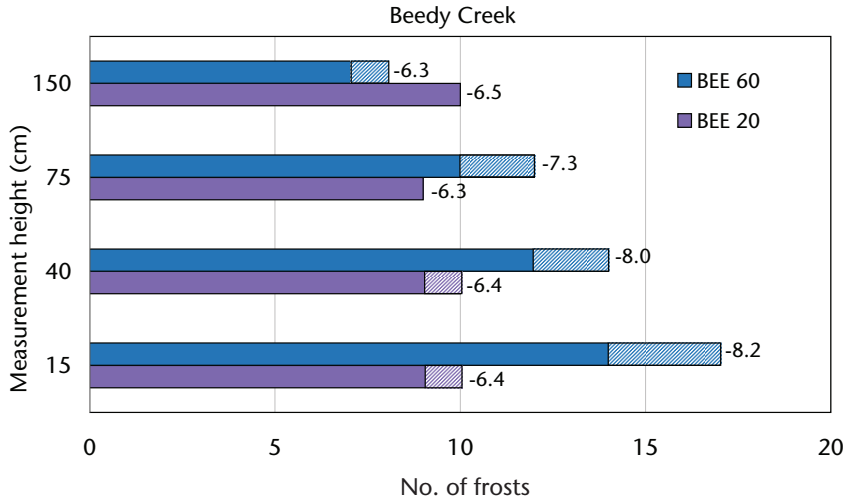


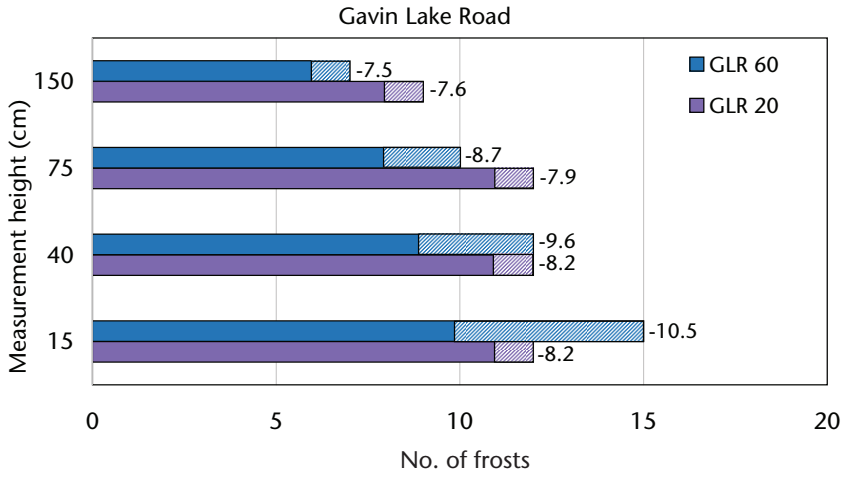




Bud flush

FIGURE 4 *Average number of seasonal frosts (2012–2016) for the bud flush (May 15–July 31) and bud set (August15–September 30) periods at each site. Bar length indicates total number of frosts. The solid bars indicate the number of frosts between 0°C and –4°C. Hatched bars indicate the number of severe frosts with air temperature < –4°C. Numbers at the end of the bars are extreme minimum air temperatures (average over three sensor arrays). Note: frost numbers were determined by averaging frost numbers from individual posts each year.*





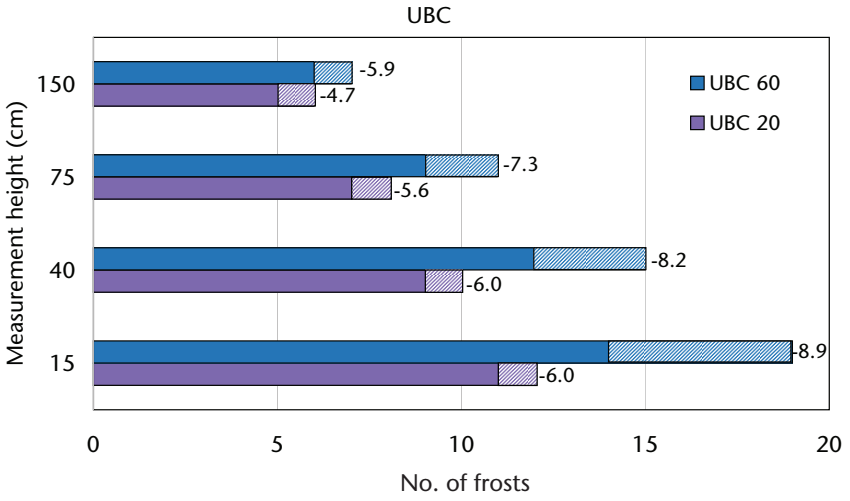


FIGURE 4 *Continued*

Bud set

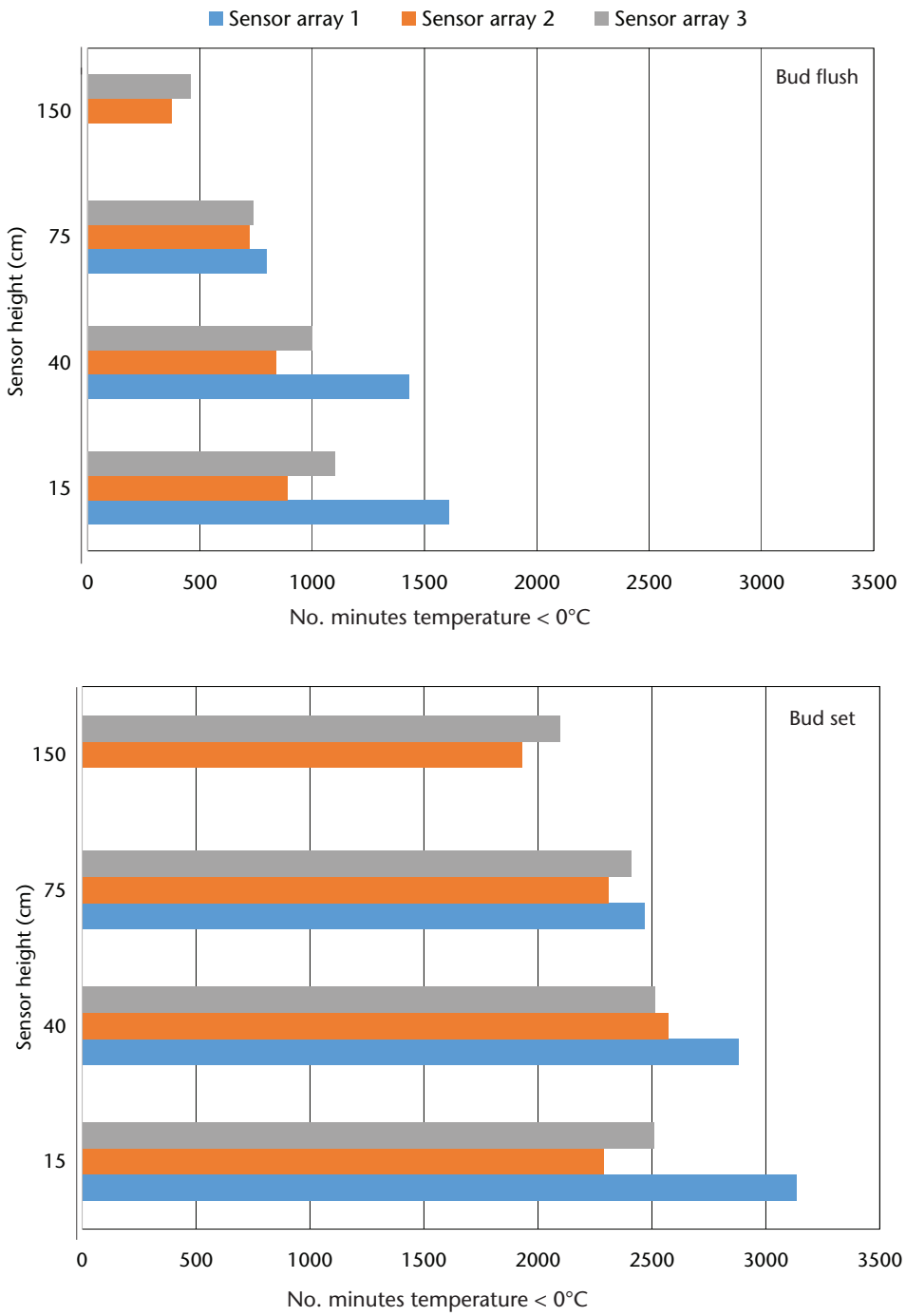


FIGURE 5 *Plot showing duration of subfreezing minutes for each sensor array post at the GLR 20 site during the bud flush and bud set periods of 2013 and 2016. Photos show each sensor array.*

Sensor array 1

Sensor array 2

Sensor array 3

FIGURE 5 *Continued*

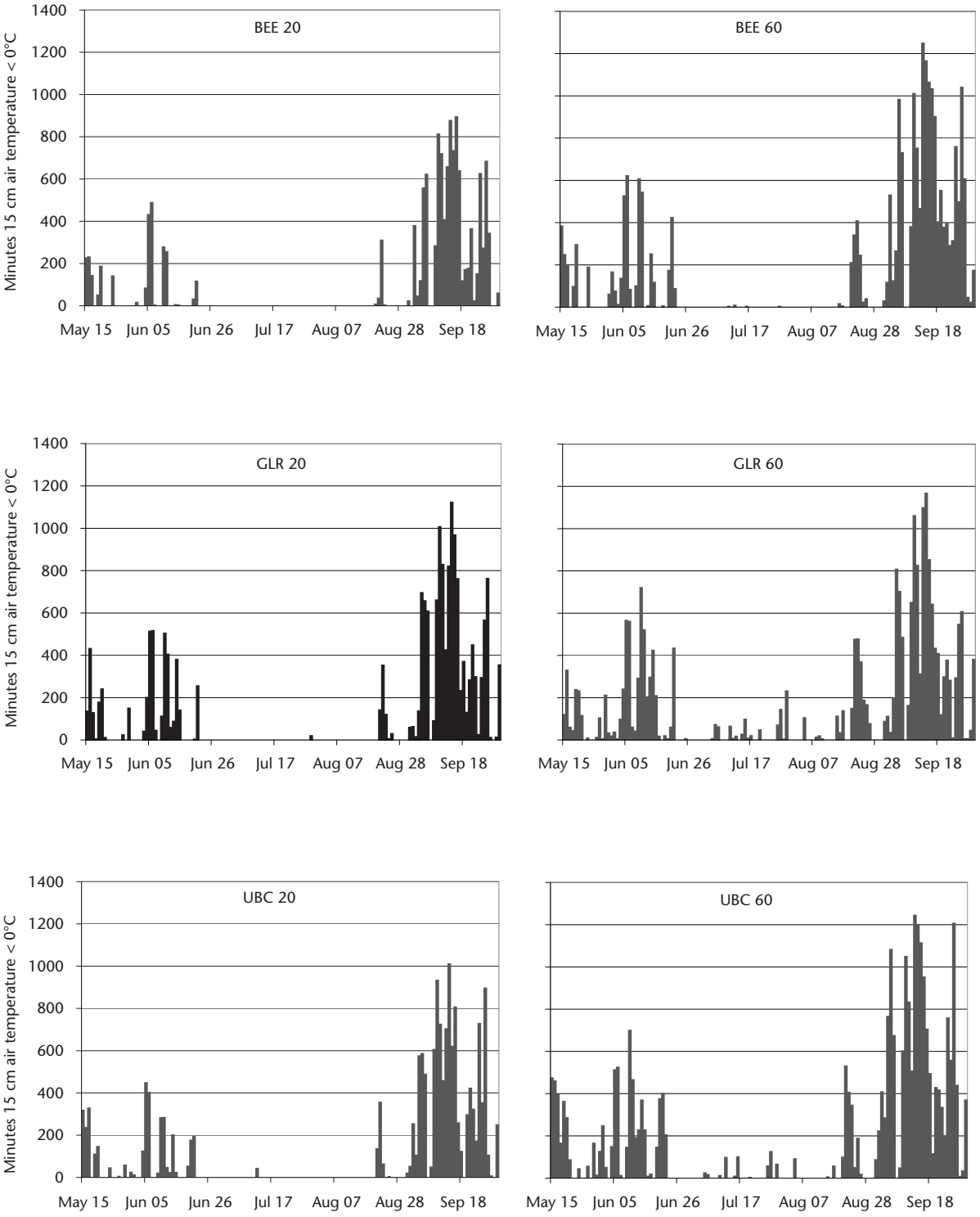


FIGURE 6 *Daily frost duration at 15 cm for each treatment totalled for the years 2012 to 2016.*

duration were shorter than found in the **60** treatment. This is a period when new growth on conifers is especially susceptible to frost damage.

Figure 7 shows a time series of vertical air temperature profiles during the night of September 9–10, 2014, which was constructed using hourly averages for the GLR **60** and **20** treatments. At 1600 hours, a lapse profile existed on the **60** treatment unit due to heating of the ground, while the profile in the **20** treatment unit was neutral due to shading, which limited heating of the air layer near the ground. By 1800 hours, a weak inversion formed in the **60** treatment unit as the ground began to cool, and there was still a well-mixed neutral profile in the **20** treatment unit. From 2100 to 0600 hours, a strong inversion formed in the **60** treatment unit, with air temperature at 15 cm as much as 3.6°C lower than that at 150 cm. In the **20** treatment unit, the profile stayed essentially neutral throughout the night, with only a very weak inversion forming in the 75–150 cm layer. There was less than a 0.5°C difference among the sensors in the **20** treatment unit in the vertical profile at 0300 and 0600 hours. At 0600 hours, the air temperature at 15 cm was –9.1°C in the **60** treatment unit compared with –7.2°C at the **20** treatment, but it was colder at 150 cm in the **20** treatment unit (–6.8°C) than in the **60** treatment unit (–5.5°C).

3.3.1 Comparison of frost statistics at Beedy Creek, 1991–2016 Air temperature data were collected during three discrete time periods at the Beedy Creek site over the course of this study: 1991–1995 (Burton et al. 2000), 2002–2008 (Sagar and Waterhouse 2010), and 2012–2016 (current study). Thus, frost frequencies in the same treatment units can be compared over time as basal area was reduced by subsequent harvest entries. Figure 8 compares the occurrence of frost events in the BEE **20** (original 70% residual basal area-fellerbuncher) as the basal area was reduced from 40 m^2/ha to 20 m^2/ha in 2001, and finally to 0 m^2/ha in 2011. As basal area was reduced, the number of frost events increased steadily from an average of one during the bud flush season in the 1993–1995 period to seven in the 2012–2016 period. A more dramatic increase in the number of frost events occurred in the **60** treatment. From the pre-harvest 1993–1995 period to the post-harvest 2012–2016 period, during the bud flush season, frosts increased from less than one per season to more than 12 per season. While the number of frost events in the BEE **20** was fairly similar to that in BEE **60** during the 1993–1995 period (no loss of frost protection by removing one-third of the basal area), it increased much more in BEE **60** by the 2012–2016 period. Increases in the number of frost events in the BEE **20** treatment as basal area decreased were moderated by the growth of natural regeneration, whereas significant advanced regeneration growth did not begin in the **60** treatment until after the logging in 2011. It should be noted that overlying large-scale synoptic weather patterns can vary from year to year and affect the number of frost events, but by averaging measurements over a number of years during comparable sampling periods, the effect of this factor on the comparisons is minimized.

3.4 Frost Damage on Planted Stock

Frost damage to planted seedlings was assessed each fall from 2012 to 2016 in the GLR and UBC **60** treatment units (Figure 9). The percentage of seedlings with foliar frost damage was low in 2012 and 2013 (< 10%), high in 2014 (64% at GLR and 38% at UBC), and moderate for the 2015 and 2016 (33% at

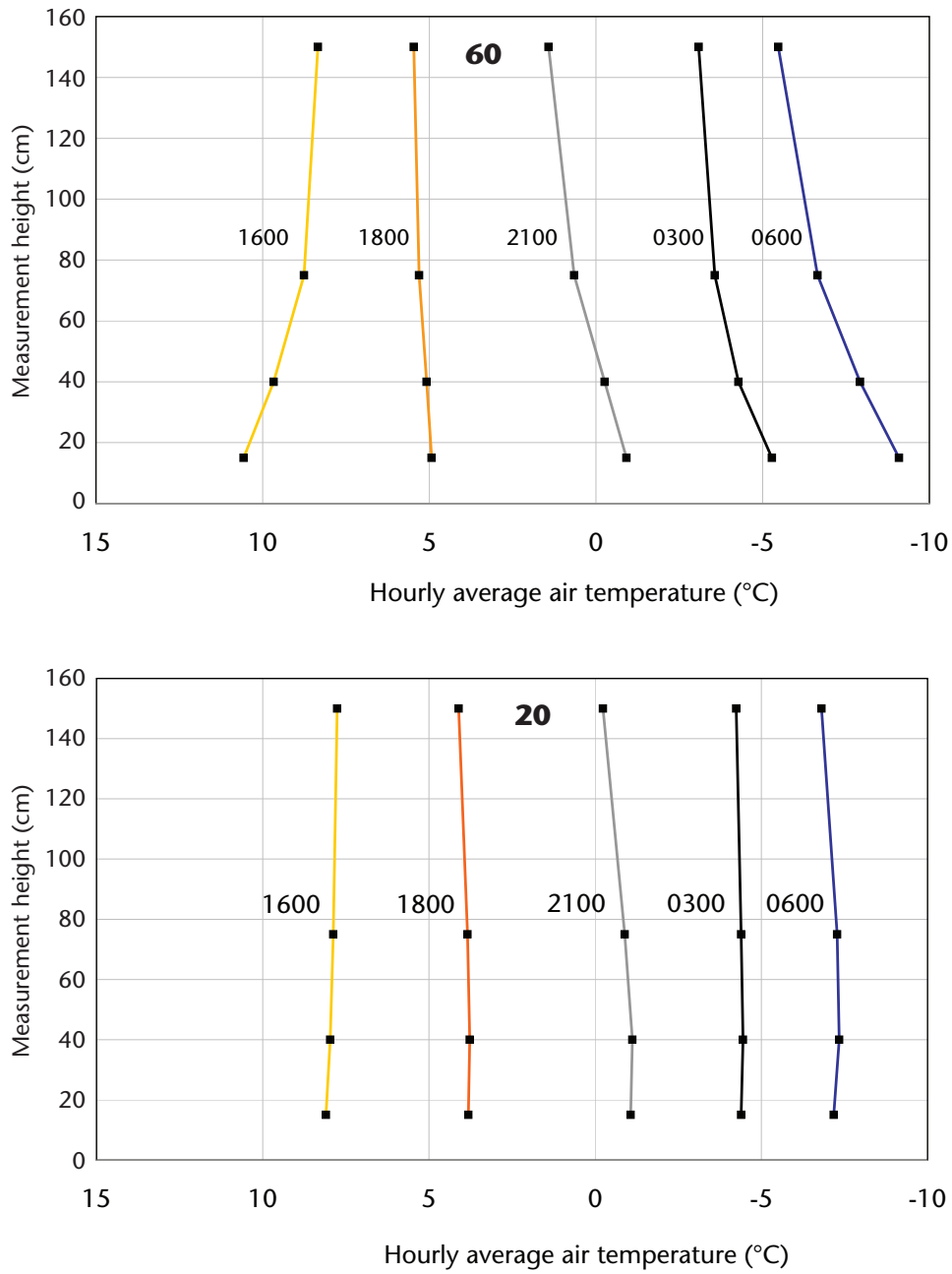


FIGURE 7 *Representative plots showing vertical air temperature profiles at the GLR 60 and 20 treatment units beginning the afternoon of September 9 at 1600 PST and ending on September 10 at 0600 PST.*

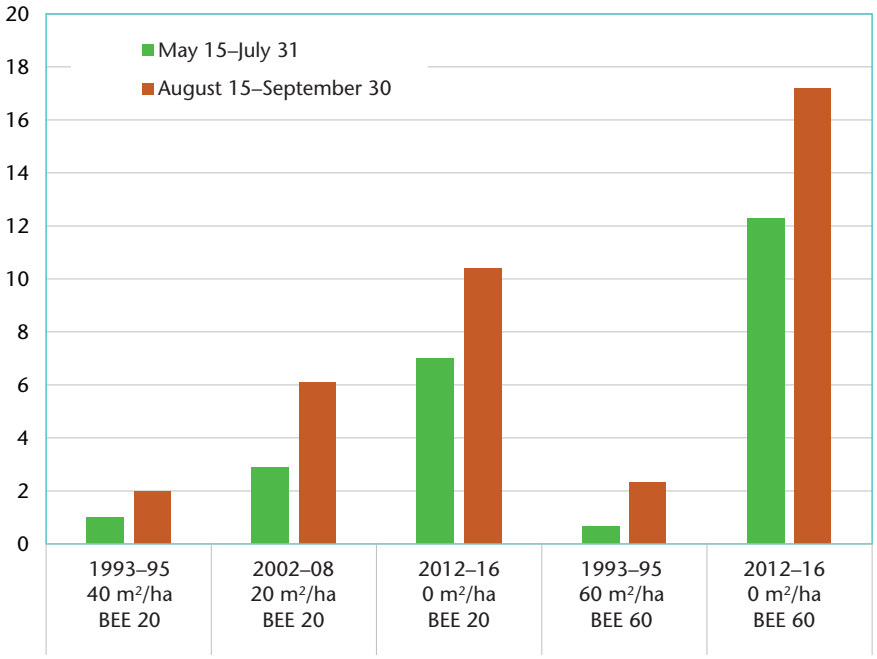


FIGURE 8 *Frost frequencies during the bud flush (May 15–July 31) and bud set (August 15–September 30) seasons for the measurement periods 1993–1995, 2002–2008, and 2012–2016 at Beedy Creek.*

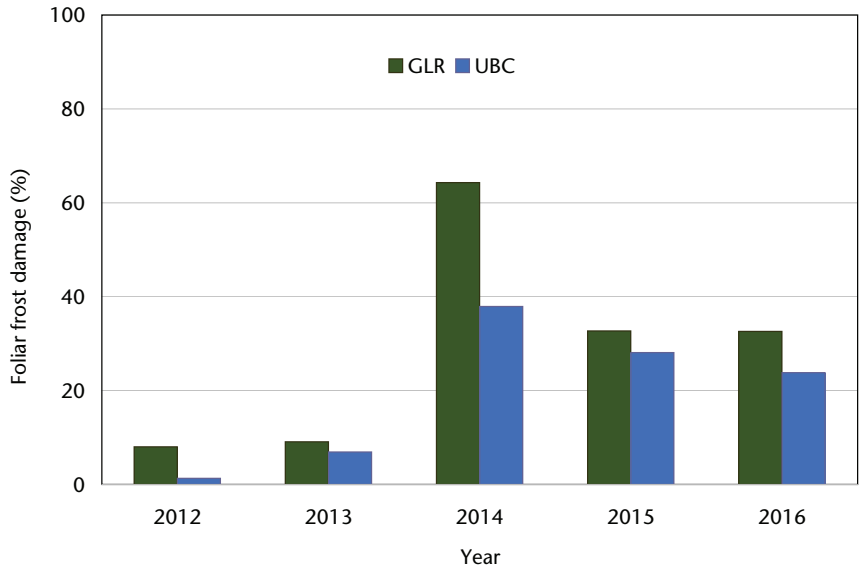


FIGURE 9 *Foliar frost damage (proportion of seedlings affected) on planted stock for the GLR and UBC 60 treatments for each year between 2012 and 2016.*

GLR and 26% at UBC) growing seasons. The high incidence of frost damage in 2014 can likely be attributed to the June 4–6 period, when severe frosts ($T \leq -4°C$) occurred each night at the 15-cm sensors at GLR and on two of three nights at UBC. On the night of June 4–5, minimum temperatures at the 15-cm sensors at GLR **60** ranged from –5.8 to –8.1°C, and the duration of subfreezing minutes exceeded 500 minutes. The 2014 bud flush period was the only one during the 5-year study in which severe frosts occurred. These severe frost events, and to a lesser extent other frost events, likely were significant factors in planted stock mortality in the GLR and UBC **60** treatments. By 2016, planted stock survival had declined to 57.8% at GLR **60** and 71.3% at UBC **60**. During the 2014 bud flush period, severe frosts occurred in every treatment except BEE **20**, which had the tallest and most developed natural regeneration of the **20** treatments (Appendix 1).

The frost statistics in Appendices 1 and 2 corroborate the pattern shown in Figure 9, with the lowest extreme minimum temperature recorded in 2014, followed by 2015 and 2016. The timing of the severe frosts in 2014 likely exacerbated the level of foliar frost damage recorded, with new bud flush being very vulnerable by early June. Had these severe frosts occurred several weeks earlier, it is possible the damage would have been more limited. Timing of bud flush may also play a factor in the different levels of damage recorded at GLR and UBC during 2014.

4 DISCUSSION

The final phase of harvesting in this trial provided an opportunity to study frost frequency and duration in the presence and absence of a well-developed shrub layer composed mostly of Douglas-fir natural regeneration. The differences in stand structure were a direct result of the experimental treatments that were implemented over a 20-year period. In the final post-harvest study, we found that frosts in the **20** treatment units were of shorter duration and extreme minimum air temperatures were higher than in the **60** treatment units. These results are similar to those reported by Sagar and Waterhouse (2015) for high-elevation clearcuts that have frequent and severe summer frost events. In that study, as the regeneration layer, mostly lodgepole pine, increased in cover and height over time (from < 1 m in the early 2000s to > 2 m by 2013), there was a corresponding decrease in the number of frost events and higher growing-season mean minimum air temperature. Both studies point to the linkage between the developmental state of the conifer regeneration layer and the frequency and duration of frost events.

Over the 2012–2016 sampling period, we found the highest incidence of frost in the recently clearcut **60** treatments, which were characterized by poor shrub development. This was similar to the results from earlier phases of the study (Burton et al. 2000; Sagar and Waterhouse 2010). The near-ground environment (15 cm above the ground) in the **60** treatments was especially harsh: with the most severe frosts, the longest duration of subfreezing minutes, and the lowest extreme minimum temperatures of any measurement location monitored in this study. Langvall and Orlander (2001) found that frost duration was an important predictor of frost injury to seedlings. The number and duration of frosts decreased with height above the

ground in the **60** treatments. The clearcut environment of the **60** treatments, in the absence of a developed shrub layer, allowed for the formation of strong nighttime inversions, with the coldest air temperatures near the ground (15 cm) and the warmest temperatures at 150 cm. Granberg et al. (1993) reported that air temperatures at 150 cm in a clearcut were warmer than at the same height in a nearby shelterwood.

To explain how shelterwoods modify inversions, Granberg et al. (1993) proposed that the overstorey trees were tall enough (20 m) to intercept sufficient wind at treetop level to force mixing to occur nearer ground, whereas in open areas, the lack of wind near the ground surface allowed inversions to form. In our study, the large Douglas-fir regeneration (5–6 m tall) in the **20** treatment was likely far below any higher strata of moving air, and was more likely within a windless layer that allowed inversions to form. Yet, the air temperature profiles were well mixed and nearly neutral from 15 cm up to at least 150 cm. So, an alternative mechanism is needed to explain the mixing. The layer of vegetation represented by the tall regeneration raises the effective radiative exchange surface from the ground level to the top of the shrub layer. Cool air forming on this surface becomes negatively buoyant and descends through the canopy, providing the mechanism for convective mixing (Stoutjedijk and Barkman 1987; Unsworth et al. 2004). This effectively mitigates the more extreme temperatures experienced near the ground (0–40 cm) by mixing colder air near the ground with warmer air above. Conversely, the colder air near the ground was mixed up to higher levels, providing a possible explanation for our observation and that temperatures at 150 cm in the **60** treatments were warmer than those at 150 cm in the **20** treatments (similar to the Granberg et al. 1993 observation for shelterwoods and clearcuts). This mixing was not present in the clearcut **60** treatments, allowing strong inversions to form.

In this study, the strength of the inversion was moderated by vegetation height and cover. The development of inversions was not limited to the **60** treatments. Moderately strong inversions also occurred in the UBC **20** treatment unit, where the regeneration layer was less developed than in the two other **20** treatment units. When air temperatures and frost statistics where averaged over all sensor arrays at GLR **20**, only weak inversions were observed. However, moderate inversions where observed at one of the three sensor arrays (array 1), which was located along a skid trail in an area with lower regeneration height and cover than at the other two sensor array posts. Our data show that on clear, calm nights, vertical temperature profiles from the ground to 150 cm can range from strong inversions to well-mixed neutral profiles, depending on regeneration height and density. Although they did not measure vertical air temperature profiles, Pritchard and Comeau (2004) found that growing-season frost incidence in small openings was correlated with stand height and density of the surrounding young aspen stands. Zasada et al. (1999) observed strong inversions forming in clearcuts, with progressively weaker and shallower inversions forming as forest cover increased from partial to full.

The comparison of frost frequency under shelterwoods of varying basal area during different periods in this 25-year study has helped us understand how shelterwood systems improve regeneration success. Reducing the overstorey basal area led to increased frost frequency and duration, as was shown in previous studies (Langvall and Ottosson-Löfvenius 2002; Sagar and

Waterhouse 2010). During the 1993–1995 period on the Beedy Creek (BEE) replicate, when basal area was 40 m^2/ha in the **20** treatment, enough light filtered in to initiate the establishment of new regeneration and some growth on existing natural regeneration, while the residual mature trees offered a high level of frost protection, similar to the uncut **60** treatment (60 m^2/ha). When basal area in the **20** treatment was reduced to 20 m^2/ha in 2001, there was a modest increase in frost frequency, but it amounted to only one-quarter to one-third of that measured in the clearcut **60** treatment (2012–2016). At about one-third of the original basal area, increased light levels encouraged the growth of already established natural regeneration, which in turn conferred some frost protection to new regeneration. When the residual basal area was reduced from 20 m^2/ha to 0 m^2/ha in 2011, a dense and tall regeneration layer was already well established. The number of frost events and their duration was far lower in the BEE **20** treatment than in the BEE **60** treatment as a result of the vigorous growth of natural regeneration in the BEE **20** treatment. Significant natural regeneration establishment and growth did not begin in the **60** treatments until after logging in 2011.

Frost was the leading cause of damage to the Douglas-fir seedlings planted in 2012, with > 60% of the seedlings at GLR **60** exhibiting signs of frost damage in 2014. The 5-year survival rate for seedlings in the GLR and UBC **60** treatments, combined, was 65.2%, with almost half of the remaining live seedlings rated as being in poor condition. Many of the seedlings in poor condition will likely die in the coming years. This amount of mortality after 5 years would cause concern for stocking, and will likely result in supplemental planting. One way to reduce the level of frost damage is by providing overstorey shelter (Sagar and Waterhouse 2010). Another possibility is through site preparation (Newsome et al. 2016).

Snowpack depth and duration, characterized by snow cessation date, may play a role in determining the risk of frost damage to planted stock. In general, a late snow cessation date will delay budburst and lessen the risk of severe frost damage. However, there are exceptions, such as in 2014, when there was a late snow cessation date followed by severe frosts in mid-June during the time of vulnerable new growth, which resulted in extensive damage to planted stock. Langvall and Ottosson-Löfvenius (2002) found that shelterwood treatments with higher basal area retention likewise delayed budburst and thus reduced the risk of frost damage.

The continued presence of a dense and tall regeneration layer with a large component of Douglas-fir on the **20** treatments post–2011 harvest confirms that the shelterwood silvicultural system was successful. The observed patterns of cover in the **20** treatments clearly show the effects of the 1991 preparatory (40 m^2 /ha retained) and 2001 regeneration cuts (20 m^2 /ha retained). Those operations made the growing environment more favourable for regeneration by allowing in more light, perhaps reducing root competition, and exposing mineral seedbeds. Regeneration in the **60** treatments started receiving more light only after the 2011 clearcutting treatment. There has been no evidence of frost damage on the natural regeneration in the final cut shelterwood treatment.[1] Much of this regeneration is > 20 years old and tall enough (at least the upper portions) to be out of the zone where severe

1 Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Williams Lake, B.C., unpubl. data.

frost could occur during the bud flush season, and in the lower zone, the frost events were substantially reduced. Also, it is possible that the shade provided by dense regeneration in the **20** treatment is beneficial when below-freezing air temperatures affect lower limbs with sensitive new buds because the shade lessens the exposure to direct sunlight. The combination of a hard frost followed by exposure to direct sunlight has been found to be especially damaging to seedlings (Lundmark and Hallgren 1987; Dang et al. 1992).

Based on their location within the SBSdw1 variant and the local topography (mostly gentle slopes and benches), all the treatments monitored during this phase of the study would be assessed as a low to medium frost hazard class according to the rating system in Steen et al. (1990). These classes apply to plantations in new clearcuts with negligible cover from natural regeneration. Based on the number of frost events observed during June, July, and August (2012–2016), the **60** treatments would likely be in the medium frost hazard class, and the **20** treatments would be in the low frost hazard class. Therefore, the presence of an overstorey or tall, developed regeneration layer can mitigate the frost hazard classification that would otherwise prevail on a site if it were a young clearcut. According to Steen et al. (1990), Douglas-fir in the medium frost hazard class can experience severe frost damage and extensive mortality, as we observed for planted stock in the **60** treatments.

Climate for the Cariboo Region (PCIC 2013) in the middle and later parts of this century is predicted to include significantly warmer summer (and year-round) air temperatures and a weaker trend toward less summer precipitation. We can speculate how these changes may affect reforestation within clearcuts and shelterwoods in the SBSdw1 variant. Warming spring and summer air temperatures do not necessarily mean that less frost damage will occur. Reduction of winter snowpacks, combined with warmer spring temperatures, may cause earlier snowmelt. The potential implications for early loss of snow cover (as was seen on the research sites during the 2015 and 2016 seasons) are earlier soil warming and an earlier start to the growing season. An earlier start to the growing season could lead to earlier budburst for natural and planted Douglas-fir regeneration and the potential for more frost damage on vulnerable conifer shoots. More important than overall warmer daily average air temperatures might be the frequency of occurrence of clear days (and nights). More clear sky conditions could increase frost frequency, despite warmer daytime air temperatures. A further possibility is earlier and more prolonged drought during mid and late summer. Earlier snowmelt in conjunction with warmer average air temperature, and possibly some reduction in summer precipitation, could lead to drier soils. Langvall and Ottosson-Löfvenius (2002) identified dry soil as a factor that causes more cooling near the ground, and thus more frost.

5 CONCLUSIONS

In new clearcuts, frost damage on Douglas-fir can range from very low to severe, and frost occurrence can range from limited to extensive in the SBSdw1, depending on mesoslope position and slope gradient (Steen et al.

1990). On new clearcuts in our study, strong temperature inversions formed, and frost was generated at ground level. Site preparation can be used to reduce frost damage and improve survival of planted stock. Alternatively, a retained overstorey canopy and/or a well-developed shrub (regeneration) layer can reduce the number of frost events, reduce the duration of frost, and raise the extreme minimum temperature. The use of an overstorey canopy to provide frost protection greatly improves the survival and growth of natural regeneration, with the added benefit of no planting or site preparation costs. The natural regeneration needs to be of sufficient size (height and cover) to moderate frost when the final overstorey removal occurs in the shelterwood silvicultural system. In our study (2012–2016), at year 21–25, after a preparatory cut, regeneration cut, and final cut, Douglas-fir regeneration was abundant and tall, and exhibited no signs of frost damage. Although climate change projections in the study area for the middle and later part of this century feature warmer annual average air temperatures, it is not known whether this will reduce the risk of frost damage to young Douglas-fir plantations.

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APPENDIX 1 *Frost statistics for 15, 40, 75, and 150 cm air temperature during the bud flushing season (May 15–July 31) for 2012–2016. Statistics include the number of minutes below freezing (no. minutes), days with minimum air temperatures below 0°C and –4°C, and extreme minimum air temperature (min. temp.). Statistics are based on the average overall sensor arrays (BEE: Beedy Creek; GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest).*

	BEE 20				BEE 60				GLR 20				GLR 60				UBC 20				UBC 60			
	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150
2012																								
No. min.	3	2	0	0	15	0	0	0	186	101	36	1	94	14	0	0	2	0	0	0	70	0	0	0
0°C	0	0	0	0	2	0	0	0	2	2	2	1	2	1	0	0	0	0	0	0	2	0	0	0
–4°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min. temp.	0.1	0.4	0.4	0.6	0.0	0.5	1.2	1.8	–1.3	–0.8	–0.7	0.0	–1.2	–0.3	0.1	1.2	0.2	0.8	1.4	2.6	–0.7	0.2	0.8	1.7
2013																								
No. min.	1023	1016	898	882	1757	1145	456	127	1310	1096	614	104	1482	683	91	0	1020	568	179	2	1644	690	118	0
0°C	12	8	8	9	12	10	8	3	12	13	10	5	17	12	4	0	9	6	4	1	15	9	5	0
–4°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min. temp.	–1.8	–1.7	–1.6	–1.7	–2.2	–1.8	–1.0	–0.5	–2.0	–1.9	–1.7	–1.0	–2.2	–1.6	–0.8	0.1	–2.2	–1.4	–0.8	0.0	–3.4	–2.3	–1.2	0.1
2014																								
No. min.	1415	1363	1225	1304	2393	1989	1207	507	2541	2394	2111	1523	2751	1910	1358	629	1663	1301	813	219	2563	1745	961	164
0°C	6	6	6	6	11	10	6	5	10	10	8	8	15	10	8	5	8	7	6	2	14	9	7	5
–4°C	0	0	0	0	2	3	0	0	2	1	1	1	4	1	1	1	1	0	0	0	2	1	0	0
Min. temp.	–3.5	–3.4	–3.0	–3.3	–5.8	–4.6	–3.6	–2.5	–5.6	–5.3	–5.2	–4.6	–6.9	–6.0	–4.9	–4.0	–3.8	–3.3	–2.9	–1.9	–5.7	–4.8	–4.1	–2.5
2015																								
No. min.	204	178	153	190	1191	482	259	16	906	1017	619	81	2684	1266	287	4	848	379	153	1	3728	1291	414	9
0°C	2	2	2	2	10	5	4	1	9	9	8	4	20	13	5	1	8	5	2	1	23	14	7	1
–4°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min. temp.	–1.2	–1.1	–0.9	–1.1	–1.9	–1.1	–0.7	–0.1	–1.6	–1.7	–1.6	–0.6	–3.4	–2.5	–1.7	–0.2	–1.4	–0.9	–0.6	0.0	–3.6	–2.5	–1.5	–0.8
2016																								
No. min.	459	430	373	443	1941	1225	642	103	1091	1085	889	725	1865	1188	549	284	1254	822	512	206	2973	1491	562	112
0°C	8	7	6	8	16	14	12	5	8	9	8	5	13	10	5	4	11	9	8	3	17	15	11	4
–4°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min. temp.	–1.6	–1.5	–1.3	–1.5	–3.1	–2.5	–2.1	–0.8	–2.2	–2.3	–2.4	–2.5	–3.0	–2.2	–1.5	–1.1	–1.7	–1.3	–1.0	–0.7	–3.8	–2.6	–1.5	–0.5

Note: Data collection for the 2012 season began from June 5 to 7 (depending on site) following new site installations. Data collection for the 2016 season ended on September 28.

APPENDIX 2 *Frost statistics for 15, 40, 75, and 150 cm air temperature during the bud set season (August 15–September 30) for 2012–2016. Statistics include the number of minutes below freezing (no. minutes), days with minimum air temperatures below 0°C and –4°C, and extreme minimum air temperature (min. temp.). Statistics are based on the average overall sensor arrays (BEE: Beedy Creek; GLR: Gavin Lake Road; UBC: Alex Fraser Research Forest).*

	BEE 20				BEE 60				GLR 20				GLR 60				UBC 20				UBC 60			
	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150	15	40	75	150
2012																								
No. min.	2667	2431	2231	1949	3696	2679	1653	522	3087	2953	2218	1196	2303	1375	846	208	1959	1149	777	190	3550	1941	605	168
0°C	14	13	12	13	18	14	12	6	16	15	14	7	14	10	7	4	12	8	5	2	18	16	7	4
–4°C	0	0	0	0	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	1	0	0
Min. temp.	–3.6	–3.6	–3.4	–3.5	–5.4	–4.5	–4.0	–3.3	–3.7	–3.9	–3.5	–3.0	–4.4	–3.5	–3.1	–2.0	–3.4	–3.2	–2.9	–1.6	–5.0	–4.2	–3.1	–2.1
2013																								
No. min.	1416	1371	1269	1239	2833	2125	1465	738	1587	1854	1492	1054	2084	1763	1223	697	1783	1500	1327	634	2482	1869	1238	523
0°C	7	7	6	7	14	12	10	4	6	6	6	6	8	6	6	4	6	6	5	4	9	7	7	4
–4°C	1	1	0	1	1	1	1	1	1	1	1	1	3	2	1	1	1	1	1	0	3	2	1	1
Min. temp.	–4.3	–4.2	–4.0	–4.2	–6.4	–5.9	–5.4	–4.4	–6.9	–6.9	–6.7	–5.9	–8.2	–7.6	–6.8	–5.6	–5.9	–5.4	–5.0	–3.8	–7.9	–7.4	–6.6	–5.5
2014																								
No. min.	2275	2214	2148	2211	4402	3398	2483	1459	3745	3554	3233	2554	4444	3257	2354	1491	3261	2761	2225	1342	5773	4406	2430	1330
0°C	8	7	7	7	18	15	12	5	13	12	12	9	13	13	11	7	11	10	8	4	22	19	12	6
–4°C	2	2	2	2	3	2	2	2	3	3	3	2	6	4	3	2	2	2	2	2	4	4	2	2
Min. temp.	–6.4	–6.4	–6.3	–6.5	–8.2	–8.0	–7.3	–6.3	–8.0	–8.2	–7.9	–7.6	–10.5	–9.6	–8.7	–7.5	–6.0	–6.0	–5.6	–4.7	–8.9	–8.2	–7.3	–5.9
2015																								
No. min.	4770	4834	4543	5166	6826	5954	5315	3595	5591	5422	5125	4581	6697	5126	4190	2973	5759	5319	4628	2433	7478	6022	4625	1613
0°C	16	16	15	16	22	20	18	15	16	17	16	15	24	20	15	14	20	18	16	14	27	19	17	14
–4°C	0	0	0	1	5	5	5	1	2	2	2	1	11	6	3	1	3	1	1	0	11	7	4	0
Min. temp.	–4.0	–3.9	–3.7	–4.1	–6.1	–5.6	–5.6	–4.6	–5.2	–5.2	–4.9	–4.3	–7.8	–6.7	–5.4	–4.6	–4.9	–4.1	–4.0	–3.1	–7.6	–6.5	–5.6	–3.1
2016																								
No. min.	2513	2516	2490	2773	4097	3530	3118	2305	3503	3457	3301	2974	5340	3893	2641	1515	3535	3198	2766	1173	6152	4745	3250	1032
0°C	7	7	7	7	14	11	10	8	11	11	11	9	15	13	10	7	11	9	8	7	19	15	12	7
–4°C	1	1	0	1	2	1	1	1	1	1	1	1	5	3	1	0	1	1	1	0	6	3	1	1
Min. temp.	–3.9	–4.0	–3.9	–4.1	–6.4	–5.8	–5.2	–4.6	–4.4	–4.4	–4.3	–4.2	–7.1	–5.9	–4.7	–3.9	–5.0	–4.4	–4.3	–3.5	–7.5	–6.8	–6.1	–4.3

Note: Data collection for the 2016 season ended on September 28.